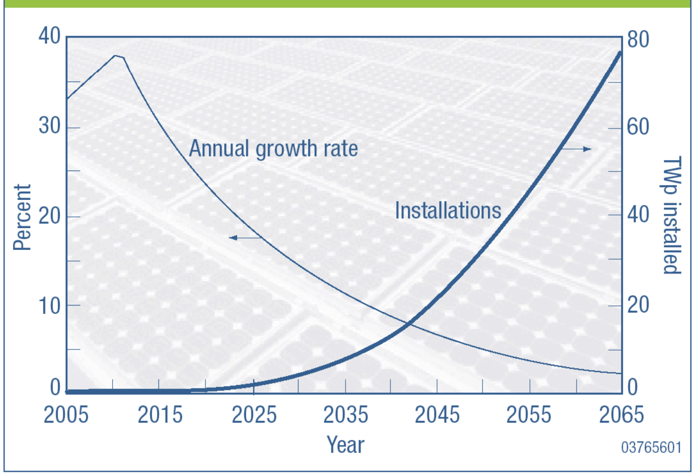
PV FAQs

Does the world have enough materials for PV to help address climate change?

In the ongoing discussion of what needs to be done to stabilize atmospheric CO_2 by mid-century (Hoffert 1998), one possible option would be to add about 10–20 terawatts (trillion watts, or TW) of photovoltaic (PV) generation capacity in place of conventional energy sources. PV would help because, unlike burning fossil fuels, it produces no CO_2. However, 10–20 TW is an enormous amount of energy to generate. In *peak watts*, as PV installations are generally rated, it is about 50–100 TW_{peak} (TW_p) of installed PV capacity.

The calculations in this FAQ are based on a goal of 75 TW_p installed by 2065. Figure 1 shows the annual growth needed to meet that goal, starting in 2004 with 1 GW_p/yr of world-wide installations (Strategies Unlimited 2005). The graph also accounts for replacing modules after 30 years of service. Based on the growth rate shown, about 830 GW_p/yr would have to be produced in 2035, and 4,100 GW_p/yr in 2065.

Figure 1. Annual PV growth rate to reach 75 TWp installed in 2065



Would we have enough materials to make this much PV? Although 75 TW_p is a vast amount of energy, we think our planet has enough feedstock materials for PV to meet the "terawatt challenge."

What does 75 TW_p really mean?

The idea of generating 75 TW_p of electricity from PV is unprecedented. Production on this level would not be "business as usual." Entire industries would be created or revolutionized. Using \$1/W_p as a round number, 75 TW_p of PV would mean \$4 trillion of annual revenue in 2065, or 10% of the world's gross domestic product (GDP) today. This seems like a large number, but if the world GDP grows 3% annually between now and 2065, \$4 trillion would only represent 2% of GDP. Additional energy will be needed to meet expanding energy needs, whether or not it comes from PV. Trillions of dollars will be spent on infrastructure and fuel, no matter how we obtain our energy.

Some 75 TW_p would require about 500,000 square kilometers of 15%-efficient modules. In terms of land area, we would need 2.5 times that area for PV installations, or a square 1,120 km on a side. This is about 0.8% of Earth's land surface. Although large, it is about the same, on a per-centage basis, as the amount we already use for national defense. It should certainly be acceptable for such a complete transformation of our energy and environmental infrastructure. For more on land space issues, please see *How much land will PV need to supply our electricity?* in this PV FAQ series.

What are the assumptions behind the numbers?

We will look at data on the materials that are necessary to manufacture PV, making certain assumptions to calculate the quantities that would probably be necessary to reach 75 TW_p of PV production.

We consider PV technologies that have already demonstrated pilot or full-scale production. Future technologies could play a major part, but we lack knowledge to estimate their materials requirements and have left them out of our calculations. Present system efficiencies are about 7%–12%; we assume an incremental increase to 15% during the next 20 years and then a stable efficiency until 2065.

To estimate commodity feedstock amounts, we conservatively assume that few technological advances will occur in packaging or structural supports of PV systems. Although unlikely, this scenario makes the point that commodity materials are not going to be a problem, no matter what the scenario (see Table 1). However, we do not include the transmission and storage technologies that would be needed to make daytime PV electricity usable when local PV production is less than demand; this is a complex system issue that we are not prepared to address here.

Will we have enough commodity materials?

Commodity materials are everyday products used in a PV system that do not relate to the actual generation of electricity within the PV module. Such materials include glass, steel, concrete, copper, aluminum, and plastic. Table 1 shows the estimated amounts that would be needed on an annual basis to reach 75 TW_p installed in 2065 (4,100 GWp/yr maximum annual PV production in 2065). We assume a steady annual growth rate of the feedstock availability, shown in the far right column.

PV will have to grow at a very high rate at first to reach 75 TW_p in 2065 (Fig. 1). During the early period of explosive growth, PV will not require significant new commodity production because existing production would still supply more of the necessary byproducts than PV could use. Thus, feedstock producers will have time to respond to further increases. No recycling of these commodity materials is assumed, although one would expect some measurable portion might be recycled. On the other hand, we do not attempt to calculate growth in demand for commodity materials outside the PV industry.

Glass sustains the largest increase over current production. However, it has no inherent limitation because it is made from silicon, the most plentiful material on Earth. Of the others, only copper may cause some long-term concern, if copper mining peaks sometime during this period (Sanden 2003). If that happens, contribution from a different conductor might be needed.

Will we have enough specialty materials?

Specialty materials are used in varying degrees within a PV module, depending on its design. Only those that might have availability issues are included in Table 2. Byproduct data are taken from Sanden (2003), which updates data from earlier studies. Recycling of process waste is assumed, meaning that 100% of process materials is used, but re-use of material from old modules is not assumed. These calculations explore the ability *of each individual technology* to produce the entire 75 TW_p of electricity individually—an unlikely scenario examined here only to display any potential limitations.

We do not consider a necessary byproduct to be constrained if 2065 amounts would require less than 200% more than today's availability, and demand is currently far below its extraction. Why? To reach 200% in 2065 is equivalent to an annual extraction growth rate of 1%, and extraction of the primary minerals (zinc, copper, aluminum) is currently growing at about 1%/yr (USGS 2003). Thus, as Table 2 shows, cadmium, gallium, and germanium are not constrained. Silicon is unconstrained because it makes up a large fraction of the Earth's crust. Molybdenum is unconstrained because there are adequate reserves—19 million MT (USGS 2004). Silver, which is used as a conductive contact, could be constrained, but adequate substitutes are likely to be found. Selenium may or may not be constrained. *Indium and tellurium are seriously constrained*, and these are essential members of copper indium diselenide (CIS) and cadmium telluride (CdTe), two crucial thin-film technologies, discussed below.

What about CIS and CdTe?

As Table 2 shows, the only constrained PV technologies are CIS and CdTe. Given the limitations of indium and tellurium, how much of these thin-film technologies could we produce? Let's get an *approximate upper limit* by assuming (1) non-PV demand would grow at 1%/yr; otherwise, all existing amounts would be available for PV use; (2) recycling of process waste would lead to 100% materials use; and (3) old modules would be completely recycled because of materials constraints.

Table 3 shows the outcome of the scenario described above. CIS could contribute as much as 17 TW_p, and CdTe, as much as 30 TW_p. Thus, these technologies together could provide roughly 60% of the 75 TW_p goal. In addition, it is important to consider that after 2065, availability issues may subside. A slower PV growth rate, the ongoing supply of recycled modules, and further PV device improvements (thinner cells, higher efficiency) might stabilize the need for newly extracted rare materials.

However, several aspects of our analysis warrant comment. First, we suggest that an increasing percentage of currently unused

Table 1. Commodity Materials: World Projected Needs Versus Current Production[a]

Material	Use in PV System	World Production[b]	Materials Required in 2065	% of Current Production	Annual Growth Needed[c]
Glass	Module (1–2 pieces)	4,100 km^2/yr	30–60x10^3 km^2/yr	730%–1,460%	3.5%–4.6%
Plastic	Module, wire connectors	40 million MT/yr	40 million MT/yr	100%	1.2%
Concrete	Pads	1.56 billion MT/yr	260 million MT/yr	17%	0.25%
Steel	Support structure	850 million MT/yr	200–400 million MT/yr	24%–47%	0.35%–0.7%
Aluminum	Support structure, wire	24 million MT/yr	5–65 million MT/yr	21%–540%	0.3%–2.2%
Copper	Wire	14 million MT/yr	9–30 million MT/yr	64%–214%	0.8%–1.9%

[a]Annual amount of materials needed to reach the peak PV production of 4.1 TW_p/yr in 2065.
[b]Annual production data from USGS (2003) and International Copper Study Group (1998).
[c]Simplified to equal growth per year between 2004 and 2065; provides the amount currently used plus the necessary additional amount. Assumes no growth in demand outside PV industry.
Notes: MT = metric tons; some of the range in copper, aluminum, and steel have to do with design tradeoffs among these metals.

Technology	Material	World Production or Byproduct Availability	Materials Required in 2065 (and Available from Recycling)	Available	Comment
Thin-film silicon	Germanium	270 MT/yr (4,000 MT/yr byproduct of zinc; 31,000 from coal)	8,000 MT/yr	23% (of total, including unused)	Not constrained if unused amounts can be refined economically
Crystalline silicon	Purified silicon[b]	30,000 MT/yr ("infinite" availability)	3.9 million MT/yr	13,000%[b]	Large growth necessary, but not availability constrained[b]
	Silver (grids/ cell pads)	20,000 MT/yr	1.25 million MT/yr	6,300%	**Borderline**, but adequate substitutes exist
Thin-film $Cu(In,Ga)Se_2$ alloys (also called CIS)	Indium	340 MT/yr (~1,500 MT/yr extractable from Zn)	23,000 MT/yr	1,500% (based on extractable total)	**Constrained**
	Selenium	2,200 MT/yr (about 17,000 MT/yr extractable copper and coal)	36,500 MT/yr	220% (of total, including unused)	**Borderline**
	Gallium	60 MT/yr (35,000 MT/yr from aluminum and coal)	3,400 MT/yr	10%	Not constrained if unused amounts can be refined economically
	Molybdenum	129,000 MT/yr	140,000 MT/yr @ 0.5 micron	110%	Not constrained
Thin-film cadmium telluride (CdTe)	Tellurium	130 MT/yr (4,000 MT/yr as byproduct of copper)	43,000 MT/yr	1,100% (of total, including unused)	**Constrained**
	Cadmium	26,000 MT/yr (40,000 MT/yr byproduct of zinc)	38,000 MT/yr	100%	Not constrained[c]

Table 2. Specialty Materials: World Projected Needs Versus Current Byproduct Availability[a]

[a]Necessary feedstocks for each type of PV technology to produce a maximum of 4.1 TW_p/yr (2.7×10^{10} m^2/yr at 15% efficiency) in 2065, to reach 75 TW_p installed in 2065, using the assumed PV growth rates of Fig. 1. Byproduct availability is included because it represents the most available source of new material—feedstock that is available but mostly unused because of currently low demand.

[b]Elemental silicon is not constrained by supply; current production is low because of low demand. Necessary amounts could be much lower with evolution of design to thin-silicon wafers or ribbons; because it is not constrained, no attempt was made to include this parameter (assumed about 1.2 kg/m^2 with losses included).

[c]Cadmium (Cd) for PV is considered by some environmental experts to be an optimum way to sequester Cd from the ecosystem. Without safe sequestration, Cd enters the ecosystem as a naturally occurring byproduct of zinc mining.

Notes: MT = metric tons. The silicon for thin-film amorphous silicon and microcrystalline silicon is not included in this table. They use 100 times less silicon than crystalline-silicon technologies, so their silicon is not a constraint. The only availability issues for thin films could be germanium and perhaps grid materials; however, most thin films do not use grids. Table 2 assumes that all 75 TW_p of energy would come from a single PV technology—an unlikely scenario.

byproduct within the primary ore would become available for future use as demand and prices climb. However, the potentially available unused byproduct amounts are uncertain: they are based on extrapolating average levels within primary ores, which may not turn out to be valid.

Second, actually processing ores to extract a higher percentage of byproduct could be an economic challenge. Extracting unused byproduct may simply turn out to be uneconomical, no matter what its value. For example, only 60%–80% of the base metal content is currently extracted. An additional aspect of the problem is that the byproducts would not be used early in the growth of PV because processing them would not yet be economical. Contrary to current mining industry procedure, that unused byproduct would have to remain available for future processing as demand increased.

A final twist on the problem is that demand for indium and tellurium could grow in non-PV applications faster than the 1%/yr growth that we have assumed. However, if indium and tellurium—which are considered byproducts—were to command high enough prices, perhaps the combined economic benefit of mining for both the primary ore and the increasingly important byproducts would create sufficient incentive to mine ores that are currently considered uneconomical.

What's the bottom line—will we really have enough materials to produce 75 TW_p of PV?

*The silicon-based materials technologies are all unconstrained by feedstock supplies and could **individually** produce 75 TW_p of clean energy.* CIS and CdTe are constrained, but could still contribute significantly to the goal for 2065. Although estab-lishing a realistic limit on the use of rare materials will require

Table 3. CdTe and CIS: Optimistic Scenario					
	Primary Metal and its Assumed Extraction Growth	Byproduct Currently Unused in Primary Metal[a] (%)	Cumulative MT by 2065; Includes Recycled Material	MT Required per TW_p	Maximum Possible CIS/CdTe Installed by 2065 (TW_p)
CIS					
Indium	Zinc, 1%/yr	77	100,000	5,600[b]	17
Selenium	Copper and coal, 1%/yr	87	2,900,000	9,000	300
CdTe					
Tellurium	Copper, 1%/yr	96	330,000	11,000	30

[a] In all cases, most of the current byproduct is unused (Sanden 2003). Additional feedstock sources, such as tellurium mines, are not considered.
[b] Indium required in devices is reduced 20% by replacing with gallium (as in some existing devices); future designs may include even larger substitutions. Assumes 15% module efficiency, 0.5-micron-thick layers. Future research may further reduce layer thickness and increase efficiencies, reducing materials demand.
Notes: This table assumes steady growth along historical lines in copper and zinc extraction. Of these, copper seems more vulnerable to slowing over the next few decades.

further analysis, new technologies that employ other materials or use rare materials more efficiently are likely to be developed, and this could also expand the potential contribution of PV to the global energy system.

A mix of PV technologies should be able to meet, or indeed exceed, the "TW challenge." In doing so, PV would provide a uniquely attractive contribution to the world's economic growth, environmental sustainability, and energy security.

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U.S. Department of Energy
Office of Energy Efficiency
and Renewable Energy
1000 Independence Ave., S.W.
Washington, D.C. 20585

DOE/GO-102005-2113
May 2005

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 20% postconsumer waste